調査

May/09/2024

動向

・Most commonly, atoms from the first two groups of the periodic table are used, since these are well- suited for cooling and trapping due to their electronic structure Ref[1].
・中性原子の計算速度を早くするために、gate を並列して作用させる動きが強まっている Ref[1]。
・quantum memory という context で、malti-level qubit が研究されている Ref[2]。

わかっていること

・Superconductors: This approach uses superconducting resonant circuits to build qubits. The circuits operate at very low temperatures, allow for fast gate operations, but currently still suffer from low coherence times and limited connectivity.
・Ion traps: These use trapping techniques to trap ions in a vacuum chamber, laser cooling techniques to cool the ions, and electromagnetic pulses in the optical, microwave, or radio frequency range to manipulate their quantum states. This approach has been successfully used to manufacture quantum computers with high levels of coherence and very high connectivity. However, calculation speed and scaling to large numbers of qubits remain a challenge.
・Neutral atoms: This approach uses laser cooling and trapping techniques for neutral atoms and manipulates their quantum states using optical or microwave pulses. It offers long coherence times, scaling in 2D or even 3D, and fair connectivities by long-range interactions (Rydberg states). The main challenges include further improvement of the two-qubit gate fidelities and gate operation speeds.
・Photons: Photonic quantum computers use light to carry quantum information, which promises very good scalability. The virtually non-existent interaction between photons imposes a challenge to implementing gate operations. Thus, most often, so-called measurement-based quantum computing is being used.
・Spins in semiconductors: In this approach, the spin of electrons or nuclei, typically in silicon, is used as the basis for qubits. It is compatible with existing semiconductor fabrication techniques, making it a promising option for scaling. However, the feasibility of such scaling concepts still has to be shown.
・NV centers in diamond: This approach uses nitrogen-vacancy (NV) centers in diamond to create qubits. The NV center is a defect that is usually manipulated using laser techniques and—at least theoretically—offers room-temperature operation.
・Cold atom-based systems typically work at room temperature, but the atoms themselves are cooled to below 1 mK using laser light Ref[1].
・中性原子の測定は、$|1\rangle$ のみを光によってぶっ飛ばし、黒い点 (何もない) になったところが $|1\rangle$、光続けているところを $|0\rangle$ とする Ref[1]。
・中性原子では single gate を複数の qubit に対して同時に作用させることができる Ref[1]。
・Rydberg state を用いると、connectivity を最大で 1:50 にすることができる Ref[1] ←!?
・Rydberg state は strong dipole moment を使うためノイズに弱い。
・The depth of the traps can be increased by changing the frequency detuning of the laser light to be closer to the atomic transition. As this in turn leads to shorter T1 decoherence times, a trade-off between these effects has to be found.
・cryostats might be used in the future to increase the qubit lifetimes, providing on-premise access to neutral atom quantum computers or integrating them into classical supercomputing centres seems to be well possible in the near future.

・現時点 (in 2023) での中性原子の性能 Ref[1]

Parameter	Typical values today (near Future)
Qubits	
Amount	~ 100 [20, 21, 22, 23] (~ 1000 for 2024 [44, 45])
Connectivity	$10:1-20:1$ [20], ($50:1-100:1$ possible in principle)
Multiple states (i.e., qudit)	In principle possible
Lifetimes and Decoherence times	
Trap lifetime	$10-60\,\mathrm{s}$ [29, 22, 30, 23] (up to $6000\,\mathrm{s}$ with cryostat [39])
Decoherence times (electronic spin)	$T_1 \sim 4\,\mathrm{s}$, $T_2 \sim 1\,\mathrm{s}$, $T_2^* \sim 4\,\mathrm{ms}$ [21, 22]
Decoherence times (nuclear spin)	$T_1 \gg 5\,\mathrm{s}$, $T_2 \sim 40\,\mathrm{s}$, $T_2^* \gg 3\,\mathrm{s}$ [23]
Native gates (gg-qubits)	
List of gates	Single-qubit rotations, *CZ* $\rightarrow$ *CNOT* [20, 38], *SWAP*, *CPHASE* [37]
>2-qubit gates:	*CCZ* $\rightarrow$ Toffoli / *CCNOT* [20, 38], C_kZ, generalisation to k control qubits [37]
Parallelism	Apply the same gate on multiple Qubits simultaneously: Single-qubit rotations, *CZ* [21] (Multiple gates on multiple Qubits)
Fidelities of operations	
1-qubit gate	$0.996-0.999$ [21, 22]
2-qubit gate	$0.955-0.995$ [38, 22, 42]
Readout	$\gtrsim 0.95$ [46]
Preparation	Trap occupation probability (after rearrangement): 0.988 [47] Success probability for defect-free array ~ 0.75, depending on size of array [47]
Execution times	
1-qubit gate	$\sim 2\,\mu\mathrm{s}$ (π-pulse) [21]
2-qubit gate	$\sim 400\,\mathrm{ns}$ (*CZ*) [21, 38]
Preparation (incl. rearrangement)	$\sim 400\,\mathrm{ms}$ [47]
Readout	$\sim 10\,\mathrm{ms}$ for fluorescence imaging [46], ($\sim 6\,\mu\mathrm{s}$ using a collective readout scheme) [46]
Installation and operation	
Required infrastructure	Vacuum cell and pumps, lasers, optical elements, microwave sources, signal generators and modulators, magnetic field coils. Cooling the setup with a cryostat can improve vacuum quality and increase trap lifetimes [39]. (Rack-level implementation possible [48])
Calibration	Rearrangement at beginning, no calibration of individual qubits necessary
Specificity	Shuttling operations [21]
Access	Via the cloud [49, 50] and on-premise
Quantum computing paradigm	Gate-based (digital) quantum computing, digital-analogue quantum computing, quantum annealing, analogue quantum simulation

問題

・様々なベンチマークが考案されているが、どの方式のハードウェアを使うかによって validity が変化してしまう Ref[1]。

・中性原子をトラップできる確率は 50〜60% しかない Ref[1]

・中性原子の並べ替えはやっぱり時間がかかる。

・中性原子の並び替えは、動かす qubit の数と動かす距離を最適化しないといけない Ref[1]

・中性原子方式は測定で原子の状態を捨ててしまうため、もう一度同じ状態を用意するためには最初からやり直さなければならない。

思考

・中性原子の冷却にかかる時間は？

・中性原子量子コンピューターでは gate 操作を同時に行うことが重要であるが、ある適用したいアルゴリズムの回路をどのように分割するかは研究の余地がある。

REFERENCES

[1] Karen Wintersperger, Neutral Atom Quantum Computing Hardware: Performance and End-User Perspective, arXiv:2304.14360v3

[2] Ming-Xin Dong, Highly efficient storage of 25-dimensional photonic qudit in a cold-atom-based quantum memory, arXiv:2301.00999v1

要調査

・超伝導やシリコンスピンで取り除かなければならない異質とは何か

・中性原子の parasitic charge とは

・中性原子の配列をグラフ理論の点に対応させることで問題を解ける

・中性原子の量子ビット再配列方法

・analog simulation の可能性

・nFT state preparation

・feedforward と mid-circuit measurement の違い

・Instataneous Quantum Polynomial

・braiding で d 以上動かすとどうなるのか

・easy intialization と difficult intialization はどっちがいいのか

・toric code in magnetic field(ising model)

・bacon-shor code

・neutral adn traped ion approaches rely on light scattering for entropy removal

・中性原子の measurement free な protocol

　・Sisyphus cooling

・cryostats